# Empirical Evaluation of V2G Round-trip Efficiency

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*Abstract*—**The business case of vehicle-to-grid (V2G) technology and its potential to provide grid services is heavily dependent on the round-trip efficiency of this technology. Surprisingly, very little empirical research is conducted to determine the V2G round-trip efficiency of electric vehicles currently available in the market, resulting in a wide range of efficiency values used in V2G modelling studies. This study aims to create more insight in the current V2G round-trip efficiency to stimulate that more uniform and realistic efficiency values are used in other studies. A field experiment is executed to measure the round-trip energy efficiency of V2G for different dates, current rates and average state of charge. It was found that the average round-trip efficiency (i.e., combined inverter and battery efficiency) when charging between a state of charge 25% and 75% with 3x16 Ampere was 87.0%(±1%). However, various external factors could influence the measured efficiencies, which had a total range from 79.1% to 87.8%. Charging at lower ambient temperatures and lower current rates had a statistically significant adverse effect on the round-trip efficiency. Efficiency at high and low state of charge was found to be marginally lower than around medium state of charges. Two different electric vehicle + charging station models were tested, one with on-board AC/DC converter, which is a novel V2G setup, and one with external AC/DC converter, rendering no statistically different efficiency values.**

*Index Terms*—**V2G, V2G efficiency, EV charging efficiency, electric vehicles, field experiment**

## I. INTRODUCTION

Vehicle-to-grid (V2G) technology is gaining prominence with increasing adoption of electric vehicles (EVs). The infeed of electricity from EV battery systems to the grid through V2G expands the opportunities of grid operators to stabilize the grid using EVs. It has been demonstrated that power quality and congestion problems in low-voltage grids can be mitigated using V2G [1], while V2G also can provide financial benefits as well as environmental benefits [2].

In recent years, multiple car models suitable for V2G have been introduced to the market (e.g., Nissan LEAF, Mitsubishi Outlander, Renault ZOE (prototype)), while charging stations compatible for bidirectional charging are now also introduced to the streets [3]. The round-trip efficiency of V2G charging cycles is crucial for future adoption of V2G, as it directly affects the business case and environmental impact of batteries in general and V2G specifically [4], [5].

An overview of the used V2G round-trip efficiencies in an non-exhaustive list of model studies in Table I indicates that the ambiguity about the efficiency is high, as V2G round-trip efficiencies range from 55% to 100%. Surprisingly, the number of empirical evaluations of the V2G round-trip efficiency is low. Refs. [4], [6]–[8] arrived at round-trip efficiency values of between 53-70%, which is low compared to the efficiency of stationary battery systems. A single measurement was carried out in [9], arriving at a round-trip efficiency of 87%. However, this study did not consider the effect of e.g. State-of-Charge (SoC), current and temperature. A laboratory experiment in [10] arrived at a round-trip efficiency of 77%, but did not use an actual EV in determining this value. Refs. [11] and [12] arrived at efficiencies of around 80%, but only considered the efficiency of the charger. The inconclusiveness on the value of the V2G round-trip efficiency among researchers is highlighted by the discussions in the following comment papers [4], [7]. Given the high importance of the V2G round-trip efficiency for future research, the current research presents a re-evaluation of the V2G round-trip efficiency in a field experiment setting, which resembles the natural environment of V2G. The V2G round-trip efficiency is evaluated for different dates, SoC, charging currents and EV charging systems. Thereby this study includes a proof-of-concept of performing V2G using an on-board AC/DC converter.

The paper is outlined as follows: Section II presents the setup of the field experiment and describes the methods used to determine the round-trip efficiency. The results of the field experiments are presented in Section III. This is placed in a wider context in the Discussion in Section IV. Concluding remarks are presented in Section V.

TABLE I
NON-EXHAUSTIVE OVERVIEW OF USED V2G ROUND-TRIP EFFICIENCIES IN LITERATURE.

| Efficiency | EV charging models |
|---|---|
| 55% | [13] |
| 72% | [14] |
| 73% | [15], [16] |
| 77% | [17] |
| 81% | [1], [18]–[21] |
| 84% | [22] |
| 86% | [23] |
| 87% | [24] |
| 94% | [25] |
| 100% | [26], [27] |

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## II. METHODS

This study used two experimental setups considering two types of charging systems, as depicted in Fig. 1a and Fig. 1b. The first experimental setup considered a charging system with the AC/DC inverter inside the charging station. A Nissan LEAF (MY2018) was charged and discharged using the eNovates DC V2G 10 kW charging station. The second experimental setup considered a charging system with a AC/DC inverter on board of the EV, using a V2G prototype of the Renault ZOE and a WeDriveSolar v1.1. charging station with a Last Miles Solutions controller. This second setup is a novel approach, which implies this research also serves as a proof-of-concept of V2G technology using the AC/DC inverter on board of the EV.

The EV batteries in both systems reported the SoC of the EV on a two second basis. Multiple charging/discharging cycles were performed, which were based on the communicated SoC of the EV battery. In a charging/discharging cycle, an EV starts charging from the predetermined starting SoC until the predetermined final SoC is reached, after which it discharges until the starting SoC is reached again. Discharging is enforced by sending a computer signal to the Open Charge Point Interface Protocol (OCPI) protocol of the charging station to change the current. Fig. 2 visually depicts the how the current translates to power, as well as the SoC during one charging/discharging cycle. In both charging systems, power flows between the charging station and the AC grid were measured on a two second basis, at the measuring point depicted in Fig. 1a and Fig. 1b. The efficiency of one charging/discharging cycle was determined by taking the ratio between the energy exported from the charging station $E_{\text{out}}$ and the energy fed into the charging station $E_{in}$ in one charging/discharging cycle, as outlined in eq. (1). Hence, the losses consist of all conversion losses in the charging station and in the EV battery in a full charging/discharging cycle. $E_{\text{in}}$ and $E_{\text{out}}$ are determined considering the charging power over time ($P_t$), the duration of one timestep ($\Delta t$), the starting moment of charging at the starting SoC ($t_{\text{SoCmin,start}}$), the moment the final SoC is reached ($t_{\text{SoCmax}}$) and the moment the starting SoC is reached again ($t_{\text{SoCmin,end}}$).

$$\eta = \frac{E_{out}}{E_{in}} = \frac{-\sum_{t_{\text{SoCmax}}}^{t_{\text{SoCmin,end}}} P_t * \Delta t}{\sum_{t_{\text{SoCmin,start}}}^{t_{\text{SoCmax}}} P_t * \Delta t} \tag{1}$$

Note that the discharging power, in the numerator of (1), is negative by convention - as also visible in Fig. 2. Therefore, the minus sign is added to obtain a positive value for the efficiency.

## III. RESULTS

Table II provides an overview of all performed tests and the average efficiency per experimental set-up. The measured efficiencies ranged from 79.1% to 87.8%. Highest efficiencies were found for the Nissan LEAF charging and discharging with the maximum current, namely $87.0\%(\pm 1\%)$. However, various external factors were found to have an impact on the efficiency, which will be discussed in the next sections.

### A. Impact of Date on Efficiency

Fig. 3 illustrates a comparison between the test results of two test; one performed on 23 April 2019 and one performed on 28 November 2019. Average efficiency of the former was 87.0%, while efficiency of the latter was 85.6%. Despite the small sample size (three and four cycles, respectively) this difference was statistically significant (two-sample t-test; $p < 0.05$).

Results could be explained by the difference in temperature between these two days; the average ambient temperature of the test performed on 23 April was 15.3 degrees Celsius, while the average of the tests performed on 28 November was 5.5 degrees Celsius. The decreased performance of EVs on cold days is a well-known factor in EV user experiences and EV modelling [28]. It is also in line with laboratory research performed on lithium-ion battery charging and discharging, which found higher heat generation (which indicates conversion losses) in the battery at low ambient temperatures than at high ambient temperatures [29].

### B. Impact State of Charge on Efficiency

Fig. 4 illustrates the efficiencies of tests performed around an SoC of 15%, 50% and 85%. Results indicate that charging efficiency is higher for medium SoCs than for SoCs either on the low or high extremes (84.6% versus 83.7% and 83.0%, respectively). For low SoCs, this is in line with previous research on lithium-ion batteries; it was found that batteries exhibit higher internal resistance and heat generation at low SoCs for both charging and discharging [29].

However, differences are relatively small and statistically insignificant. This illustrates that V2G can also be performed for low and high SoCs of the EV without compromizing on the efficiency.

### C. Impact Current on Efficiency

Fig. 5 illustrates the various efficiencies on full load and partial load. Partial load (3x8A) significantly reduces the round-trip efficiency of V2G (two-sample t-test, $p < 0.01$). Decreasing the current to 3x4A further decreases the efficiency.

These results are not in line with [29], who found that heat generation in batteries (which indicate losses) increase with increasing current. However, the C-rates (i.e. power-to-energy ratio) in that study were between 1 and 4, whereas C-rates were below 1 in our study, which makes results incomparable.

### D. Impact EV and Charging Station Type on Efficiency

Fig. 6 compares the efficiencies of the two tested charging systems. Results indicate that similar efficiencies can be obtained with different V2G configurations. As the AC/DC converter of the Renault ZOE is still a prototype, better efficiencies can potentially be obtained with further development of the technology.

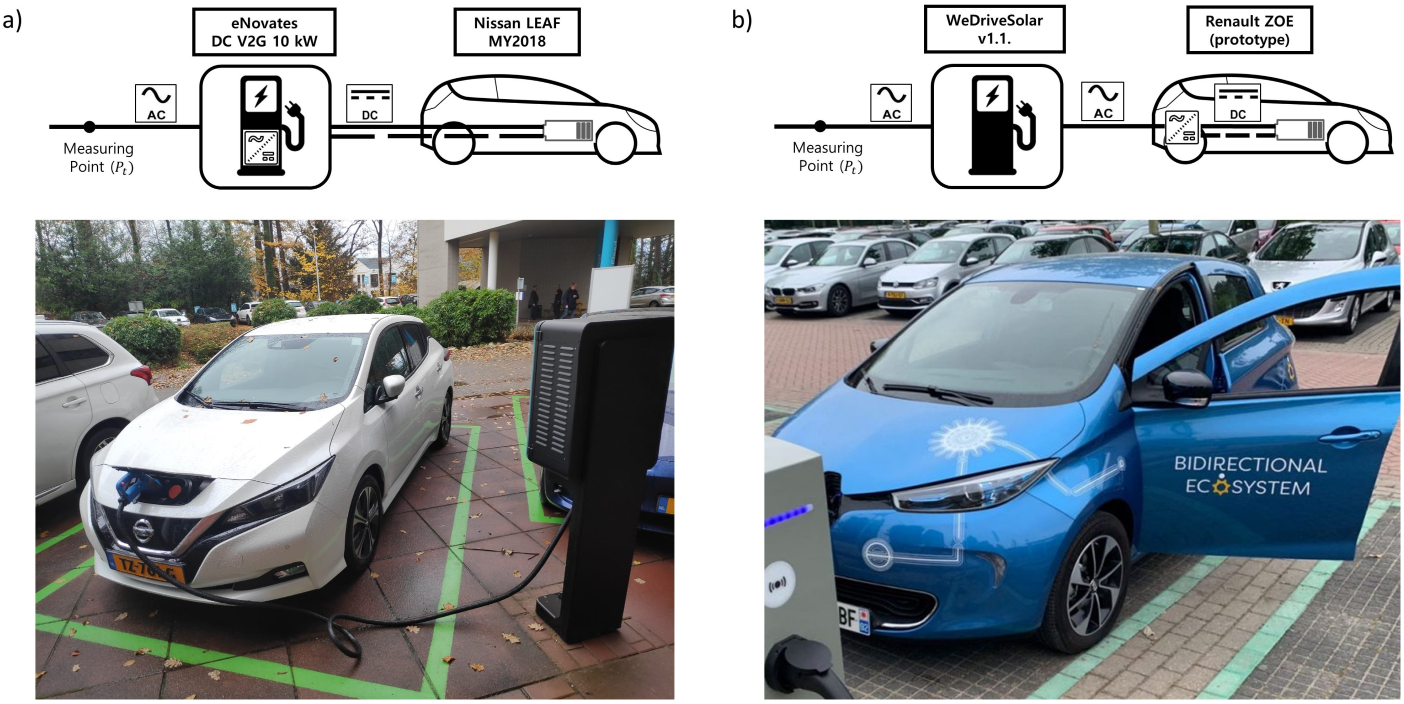

Fig. 1. a) Experimental setup of V2G measuring system with AC/DC inverter in the charging station, using a Nissan LEAF. Image of Nissan LEAF is taken at testing lab of ElaadNL. b) Experimental setup of V2G measuring system with AC/DC inverter onboard of the EV, using a Renault ZOE prototype. Image of Renault ZOE is a stock photo from Renault.

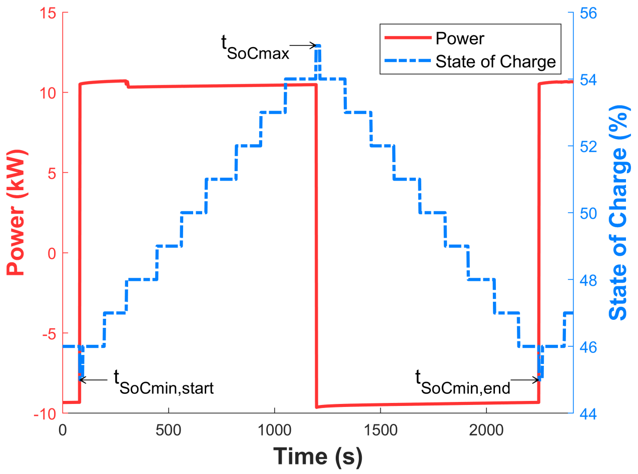

Fig. 2. One charging / discharging cycle, in this case between a SoC of 45% and 55%. The start and end times of a half cycle are indicated by $t_{\text{SoCmin,start}}$, $t_{\text{SoCmax}}$ and $t_{\text{SoCmin,end}}$. Note that the EV only communicates integers, which explains the step-wise increase in SoC.

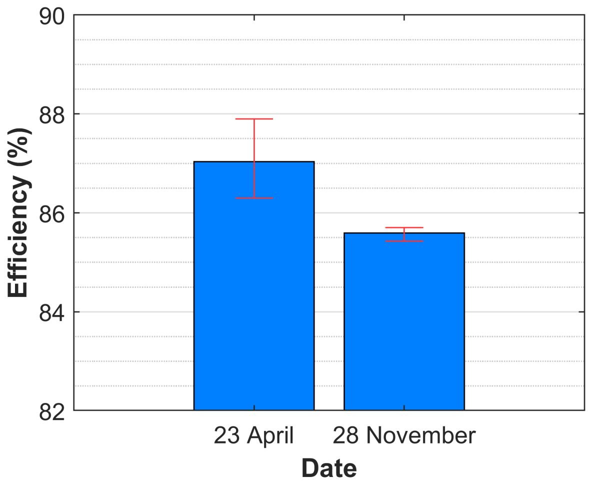

Fig. 3. Efficiencies of tests performed in spring and in late autumn, with SoC range 25% to 75%. Height of bars indicate the average of the tests; error bars indicate the minimum and maximum found efficiency within the tests.

### E. Charging and Discharging Power at Different SoCs

Fig. 7 illustrates the relationship between SoC and power for charging and discharging (V2G) of the Nissan LEAF. In general, power rates of charging are somewhat higher. This is because of the location of the measuring point, which is between the charging station and the AC grid. Hence, charging power rates are before conversion losses and discharging rates after conversion losses. What further stands out, is the jagged shape in the charging curve - despite the current signal that is sent to the charging station is constant. Apparently, either the charging station or the EV readjusts the voltage at specific

TABLE II
OVERVIEW TEST RESULTS.

| **Start Time** | **End Time** | **Current** | **SoC limits** | **EV + EVSE** | **Number of cycles** | **Average Efficiency (AC-to-AC)** |
|---|---|---|---|---|---|---|
| 23/04/2019, 18:17 | 24/04/2019, 07:33 | 3x16A | 25%-75% | Nissan LEAF + eNovates | 4 | 87.0% |
| 28/11/2019, 19:22 | 29/11/2019, 04:53 | 3x16A | 25%-75% | Nissan LEAF + eNovates | 3 | 85.6% |
| 1/05/2019, 15:30 | 2/5/2019, 06:31 | 3x8A | 30%-70% | Nissan LEAF + eNovates | 3 | 84.6% |
| 24/04/2019, 16:02 | 25/4/2019, 05:02 | 3x4A | 25%-75% | Nissan LEAF + eNovates | 1 | 79.2% |
| 28/11/2019, 10:06 | 28/11/2019, 12:04 | 3x16A | 80%-90% | Nissan LEAF + eNovates | 3 | 83.0% |
| 28/11/2019, 13:21 | 29/11/2019, 10:31 | 3x16A | 45%-55% | Nissan LEAF + eNovates | 3 | 84.6% |
| 28/11/2019, 15:29 | 28/11/2019, 16:50 | 3x16A | 11%-19% | Nissan LEAF + eNovates | 3 | 83.7% |
| 9/10/2019, 11:31 | 9/10/2019, 14:49 | 3x16A | 25%-35% | Renault ZOE (prototype) | 3 | 85.1% |

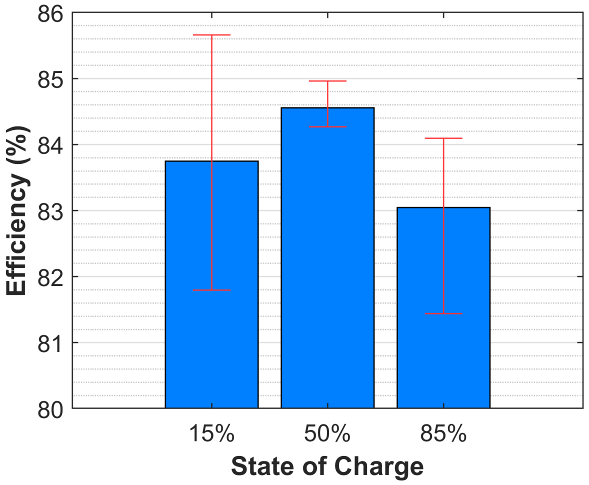

Fig. 4. Efficiency at different average SoCs, with SoC range of 11% to 19%, 45% to 55% and 80% to 90%. Height of bars indicate the average of the tests; error bars indicate the minimum and maximum found efficiency within the tests.

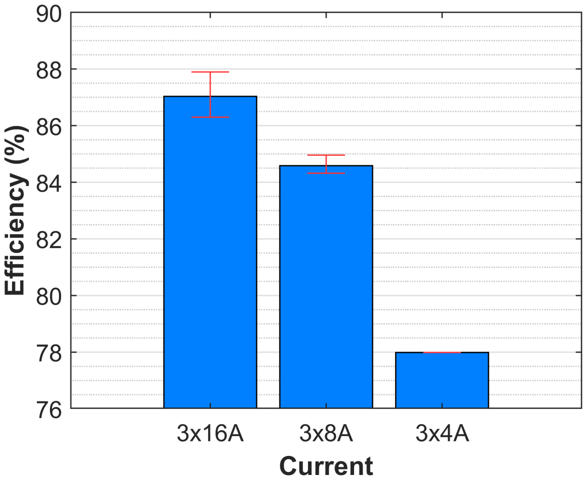

Fig. 5. Efficiencies of tests for different values of current, with SoC range of 25% to 75% for 3x16A and 3x4A and 30% to 70% for 3x8A.. Height of bars indicate the average of the tests; error bars indicate the minimum and maximum found efficiency within the tests. The test of 3x4A was performed only once, hence the non-existent error bar.

SoCs. A possible explanation is that the EV some modules of the battery pack are charged consecutively instead of in parallel, however, the underlying reason is difficult to verify. The discharging curve follows the more well-known power curve of a battery, with higher voltages at higher SoCs [30].

## IV. DISCUSSION

In total, the round-trip efficiency of 23 full V2G charging + discharging cycles was determined. A maximum efficiency of 87% was found. This value is in line with the values reported in [9], but substantially higher than the highest reported V2G round-trip efficiency in multiple other studies [4], [6], [10], [11]. These higher reported efficiency values indicate that other studies assuming a considerably lower efficiency values might have underestimated the business case and potential to provide grid services of V2G.

Lower temperatures and partial load seem to have a significant negative impact on V2G round-trip efficiency. The considerably lower efficiency values with partial load has considerable implications for EV charging models. Where most EV charging models consider that the charging and discharging efficiency is independent of the charging load, this study indicated that this assumption is invalid. It is recommended that the dependency between charging current and charging efficiency is considered in future charging models.

It should be noted that the experimental setup was a field experiment, which is both a strength and a weakness of the present study. The disadvantage of this setting is that it is impossible to make conclusive statements on the relation between independent and dependent variables. The advantage is that this setting resembles the natural environment of V2G, increasing the external validity of the tests.

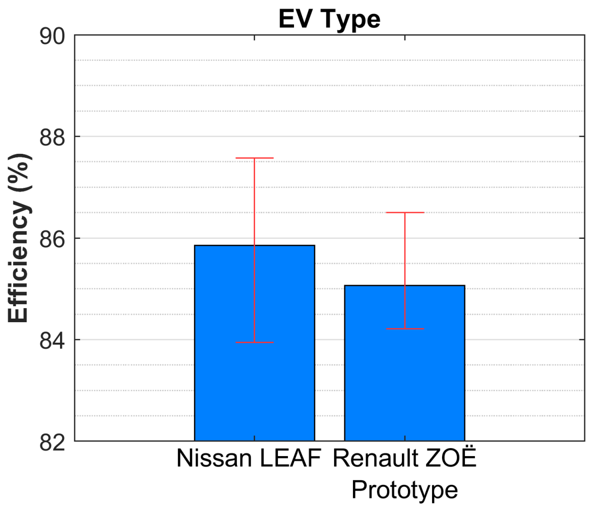

Fig. 6. Efficiencies of the Nissan LEAF (MY2018) combined with the eNovates DC V2G 10kW charger, with SoC ranges between 25% and 75% and the Renault ZOE with on-board AC/DC converter (prototype), with SoC range of 25% to 35%. Height of bars indicate the average of the tests; error bars indicate the minimum and maximum found efficiency within the tests.

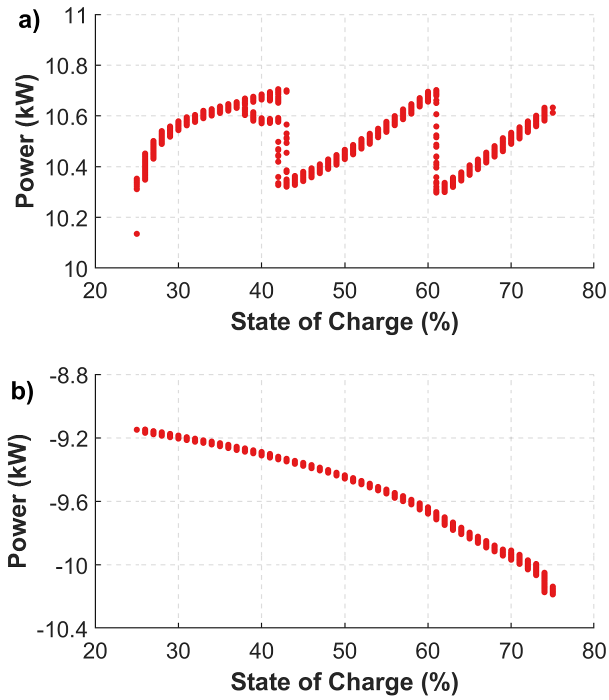

Fig. 7. State of Charge versus **a)** charging power and **b)** discharging (V2G) power of EV of three charging cycles at 3x16 Ampere of the Nissan LEAF between SoCs of 25% and 75%.

Inaccuracies in measurements could occur from the communicated SoC by the EV battery. An important factor for the EV to determine its SoC is the voltage level in the battery system. However, the voltage in the battery can also be affected by different parameters, including the battery temperature and previous operation history [30]. Therefore, the same reported SoC does not necessarily represent the same energy level in the battery. By performing multiple charge and discharge cycles of a large SoC-range, the effect of this potential inaccuracy is minimized.

Our results have important practical implications. Since the efficiencies reported in this study are determined in a field experiment, results give a realistic estimation of V2G efficiencies in real-world applications. As mentioned before, efficiency is of large importance for the financial and environmental impact of battery operation in general, and V2G specifically [4], [5]. Aggregators could use the efficiency values obtained in this research to explore V2G business cases for EV users. Also, the environmental impact of V2G can be determined more accurately, with important implications for policy makers in determining the role V2G can play within the energy transition.

## V. CONCLUDING REMARKS

This study was the first to perform a more broad field experiment on the round-trip efficiency of V2G. Furthermore, it provides a proof-of-concept of V2G using the AC/DC inverter on board of the EV. The results give guidance to EV modellers on appropriate efficiencies to assume and important impacting factors.

Future research could perform more sophisticated analyses on the V2G round-trip efficiency by performing more charge and discharge cycles, by considering more charging stations and more EV types. In addition, future research should implement power flow meters behind the inverter to be able to separate V2G efficiency losses into battery losses and inverter losses. Also the range of experiments can be extended by testing other potential impacting factors like different weather conditions and battery age.

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